Coupling of airborne sound into the arth: Frequency d p ndence

H. E. Bass and L. N. Bolen

Department of Physics and Astronomy, The University of Mississippi, University, Mississippi 38677

Daniel Cress, Jerry Lundien, and Mark Flohr

Mobility and Environmental Systems Laboratory, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi 39180

(Received 5 June 1979; accepted for publication 11 January 1980)

Simultaneous measurements have been made of sound pressure above the ground and seismic velocity below the ground surface resulting from a source suspended in the air a variable distance from the surface. The ratio of seismic velocity to acoustic sound pressure has been determined; there are peaks in the ratio in the vicinity of 45 and 90 Hz depending on the height of the speaker. The source–receiver distance was 10, 30, and 60 m; the source height was varied between 1 and 10 m. The frequency of maximum acoustic coupling was found to agree well with theory; the first and third shear modes appear to be excited. Results for vertical, horizontal, and radial motion indicate the coupled seismic signal is greatest for vertical, next greatest for radial, and least for transverse, though the difference between radial and vertical displacement velocities was not great and depended on the speaker altitude.

PACS numbers: 43.28.Hr, 43.40.Ph

INTRODUCTION

The coupling of airborne sound into the earth has received only sporadic attention since the pioneering work of Lamb.[1] A series of papers by Press and co-workers[2-5] in the early 1950s did much to explain seismic signals resulting from airborne blasts. They found that airborne blasts typically excited ground vibrations at a frequency such that the dispersive seismic velocity matched the speed of sound in air. The equations for the frequency of maximum coupling to seismic modes were solved for a ground plane composed of two elastic layers and a liquid layer over an elastic solid. Measurements of the sound coupled into a sheet of floating ice agree well with theory. More recent work has been concerned with seismic disturbances resulting from shock waves resulting from supersonic aircraft.[6-8] In this case, the effective speed of the disturbance across the earth varies with aircraft speed and direction with respect to the horizontal.

The work reported here was designed to determine the coupling into the earth as a function of frequency in the range 20–300 Hz with varying source–receiver distances and source heights above the surface. The frequency at which maximum coupling occurs will be the subject of this paper; comparison of the magnitude of the seismic signal to theory will require more extensive theoretical work.

I. EXPERIMENT

Two series of measurements were made on the same site at the Waterway Experiment Station at Vicksburg, Mississippi. The test site is relatively flat with a gradual drop in elevation from south to north of approximately 1 m per 100 m. The surface soil is a brown to dark brown heavy, silt loam (CL). The texture of the subsoil ranges from heavy loam (CL) to silty clay loam (CL). Seismic shear and compression velocities were measured using standard seismic refractions techniques.[9] The seismic survey indicated a surface layer 5.3–6.9 m in depth with a compression wave velocity of 340–350 m/s and a shear wave velocity of 150–160 m/s. The underlying layer had a compression wave velocity between 950 and 2000 m/s. This variation was possibly due to variable water content in the lower layer.

The experimental layout is shown in Fig. 1. Location 2 was not used in the first series of tests. The sound was driven by a large bass-reflex speaker system driven by a 175-W amplifier. Seismic response data were measured using Mark Products L-4A-3D scientific triaxial geophones; these geophones are suspect above 100 Hz. They were buried with approximately 5 cm of soil on top to keep the ground surface smooth. The acoustic sound pressure was measured with broadband capacitance-type microphones. Microphone heights were varied between 0 and 2 m. All signals were recorded

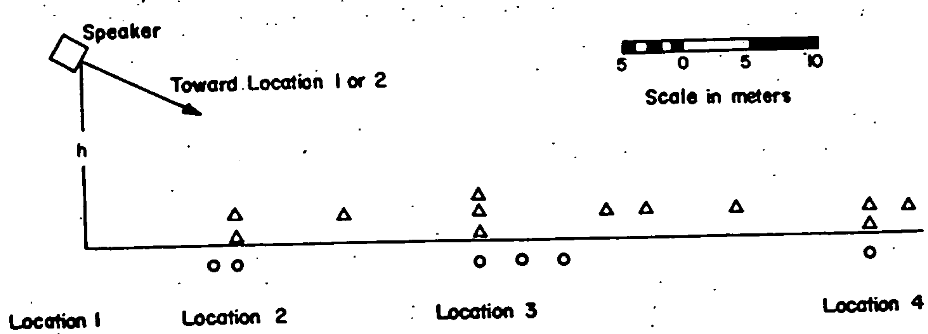


FIG. 1. Test site layout; △ represe[nts] microphones; O represents geophon[es].

on a 14-track FM tape recorder with a frequency response fr m 0 t 2500 Hz running at 7 ½ ips. The analog signals were digitized before analyzing the data at a rate of 5000 samples p r second. The signal f r th source was band-limited pink noise and a swept frequency between 20 and 700 Hz.

The source height was varied by hoisting the speaker with a crane. By suspending the speaker from a single cable, coupling from the speaker through the support into the ground was eliminated.

I. EXPERIMENTAL RESULTS

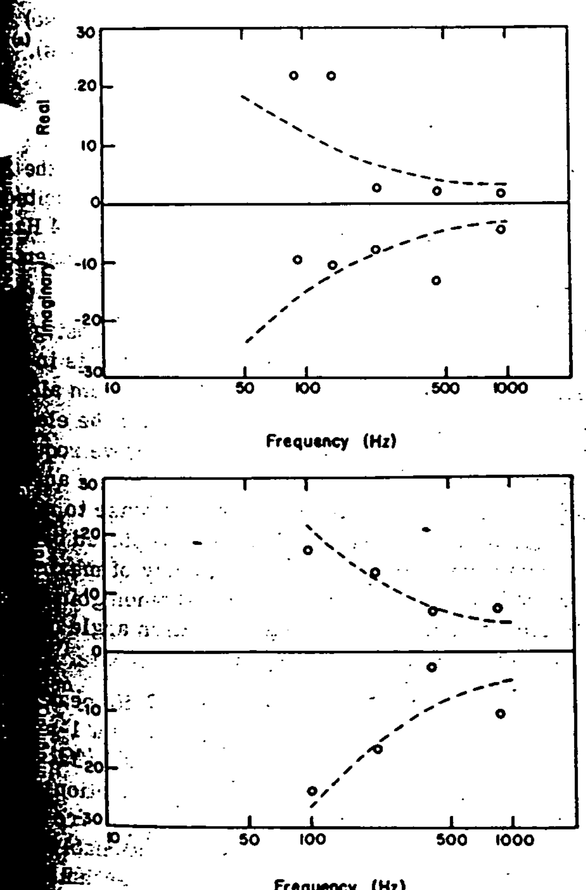
These measurements provided three separate pieces of information which will be discussed here: the surface impedance of the test site, the ratio of seismic to acoustic signal strength, and the dependence of this ratio on angle of incidence of the incoming wave (speaker height).

The results of surface impedance measurements are presented in Figs. 2(a) and 2(b). Sound amplitudes during test I were made at positions 3 and 4 for microphone heights between 0 and 2 m in 6-in. intervals. For test II, heights of 1 and 2 m were employed. As a result, th first series of measurements yielded more data to be used in determining surface impedance and exhibit less scatter. Impedance values were determined using the theory of Donato.[10] The method used to extract impedance values from measured amplitude as a function of receiver height and distance is discussed in detail in Ref. 11. The curves in Fig. 2 wer comput d from th equations developed by Chessell[12] using values of specific flow resistance given in the figures.

The ratio of seismic particle velocity to acoustic sound pressure was termed the coupling coefficient given in units of cm/s per μbar. Results for typical swept frequency tests are presented in Figs. 3(a) and 3(b). For both cases, the speaker was 2.44 m above the surface. Note that for both tests maxima in the coupling coefficient occur near 40 and 90 Hz.

Similar results are given in Fig. 4(a) where excitation was provided by band-limited pink noise (45–90 Hz) centered at 63 Hz. Figure 4(a) gives results for vertical particle seismic velocity, Fig. 4(b) for radial seismic particle velocity. Note that the peaks near 40 and 90 Hz appear for both directions of motion though the peaks in the radial displacement are not quite so large. The radial geophone also shows a lower-frequency coupling coefficient peak; this lower-frequency peak has not been studied in detail. Transverse displacement velocities showed similar frequency dependence with a magnitude lower than that of the radial coupling.

Figures 5(a)–5(e) show the shift in the peak near 50 Hz as a function of speaker height. The frequency axis for these figures is expanded relative to previous fig-



Normalized surface impedance ($Z/\rho_0 C$); (a) test I; line computed with $\sigma = 300$ g cm^{-3} s^{-1} using theory of (b) test II; dashed lined computed with $\sigma = 130$ s^{-1}.

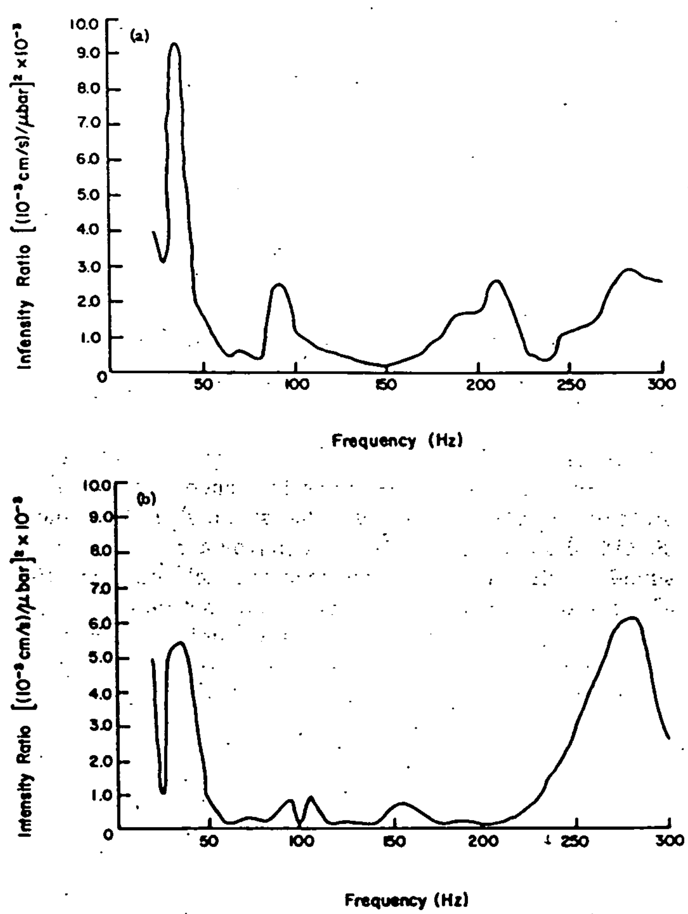


FIG. 3. Seismic/acoustic coupling coefficient for swept frequency; (a) test I; (b) test II.

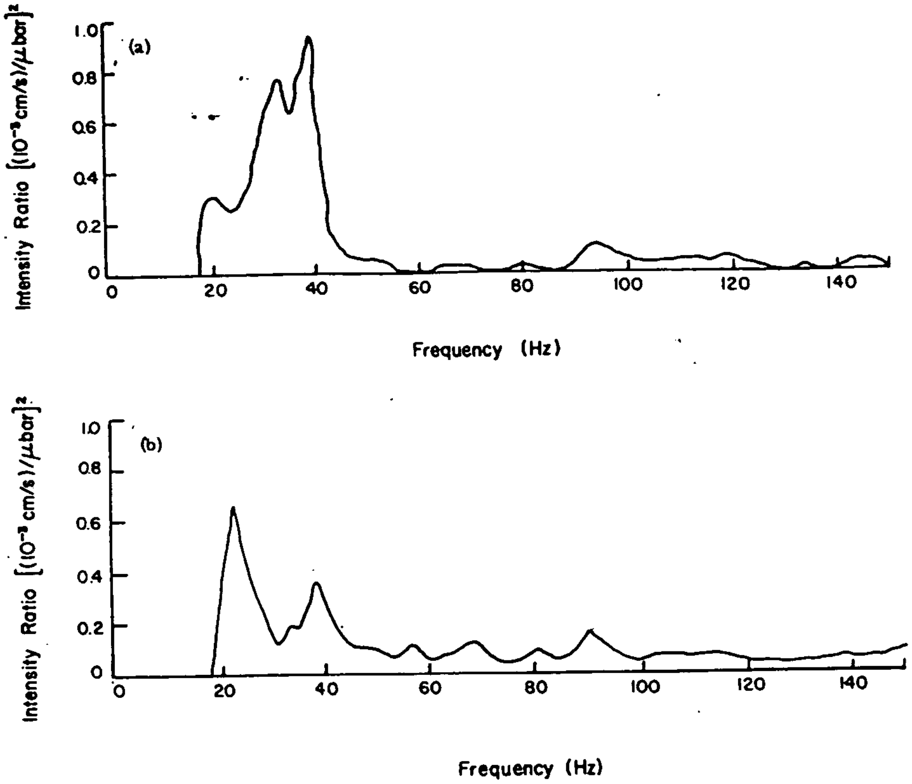


FIG. 4. Seismic/acoustic coupling co- efficient for band-limited pink noise (63-Hz octave band); (a) vertical dis- placement; (b) radial displacement.

ures. Although the peaks in coupling are not so well-defined on the expanded scale, there is a definite (though not uniform) shift in the frequency of maxium coupling as the speaker height is increased from about 57 Hz at a 1-m height to 42 Hz at 10 m. These data were collected at the 10-m poisition so the nominal angle of incidence varied from 5° at a 1-m height to 45° at 10 m. There is a difference between the frequency of maximum coupling at a speaker height of 2.44 m at the 10-m location as compared to the results presented earlier for the 30-m location. This difference can only partially be attributed to a different layer thickness (5.3 m at location 2, 6.1 m at location 3).

III. DISCUSSION OF RESULTS

The surface impedance measurements suggest that the porous soil has a significant influence on the coupling process even at 40 Hz. The static soil impedance should be about 10^3 greater than ρc for air, but the measured specific surface impedance is much less than 10^3. The relatively thin porous layer would not be expected to affect the frequency of maximum coupling so much as the amplitude. Since the equations for the amplitude of the waves coupled into the earth have not yet been solved, we can only speculate that the porosity of the surface will affect this amplitude.

The frequency of maximum coupling into the earth can be predicted based on the work of Espinosa, Sierra, and Mickey[6] for coupling of sound into a waveguide f rmed by the ~6-m-thick surface layer. Following the notation of Ref. 6, the critical angle for coupling is

$$\sin\phi_c = V_\beta/V_\alpha , \qquad (1)$$

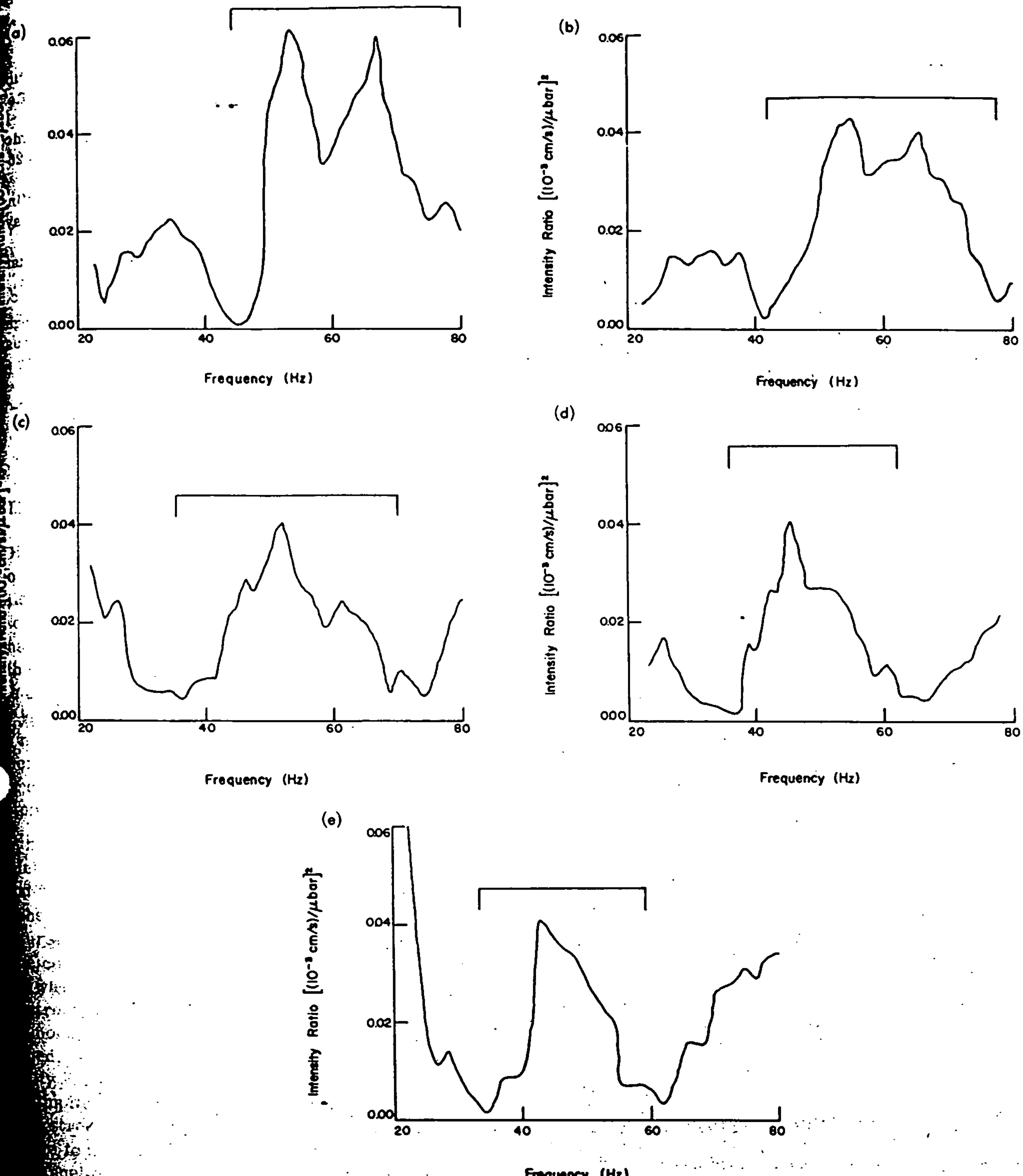
where V_β is the shear velocity (160 m/s for our case) and V_α is the compressional wave velocity (330 m/s). For constructive interference,

$$f_a = (\eta+1)c/2H\cos\phi , \qquad (2)$$

where H is the thickness of the surface layer, c is the speed of sound in air, and η is the mode numb r excite For our case, with $\eta=0, f_a=32$ Hz; for $\eta=1, f_a=64$ Hz and with $\eta=2, f_a=95$ Hz; the sweep tone measurements show peaks near 32 and 95 Hz.

The effect of speaker height can be estimated using the same approach. As the height of the source is increased, the distance between pressure maximum alon the surface will decrease as $\cos\theta$, where θ is the elevation angle. For constructive interference, we requi that pressure maxima occur at the same interval acro the surface, hence the frequency must decrease to maximize coupling. If c in expression (2) is replaced by $c\cos\theta$, for a given value of η, the frequency of maxim coupling should shift by a factor of 1/1.4 when going from an elevation angle of 5° to an elevation angle of 45°. The measured factor is 1/1.38.

There is also a systematic shift in the 67-Hz peak the source height is increased: from 67 Hz at a 1-m height to 58 Hz at 10 m. This shift represents a facto of only 1/1.2 suggesting that the simple explanation u for the 50-Hz peak will not suffice. The higher-frequency peaks shown in Fig. 2 do not shift noticeably with elevation angle suggesting a different mechanism for coupling of s und at these frequencies. It is possi ble that these high-frequency peaks involve a resona in the geophone; the wavelength is about twice the ge phone length.



Seismic/acoustic coupling coefficient for different source heights; test II; (a) 1 m, (b) 2.44 m, (c) 5 m, (d) 7.5 m,

CONCLUSIONS

frequency of maximum ac ustic coupling into the can be understood in terms of excitation of nor- urface m des. Although this simple theory pro- reasonable agreement with the measured frequen- maximum c upling, it does not include the effects pper porous layer. This fact suggests that the frequence dependence of the coupling is not affected by the porous layer. One cannot conclude, however, that the porous layer does not affect the magnitude of the coupling. Measurements of vertical, radial, and transverse seismic velocities suggest that the ordering of magnitude found in Ref. 8 is reproducible; some change in the relative magnitude of the vertical and radial displacement velocities with nominal angle of incidence was observed.

ACKNOWLEDGMENTS

Th authors wish t acknowledge the financial support f Sandia Laboratories and the Army R search Office. Data collection was under the supervision of Mr. Joe Savage of WES.

[1] H. Lamb, "On the Propagation of Tremors over the Surface of an Elastic Solid," Philos. Trans. R. Soc. London Ser. 203, 1–42 (1904).

[2] F. Press and M. Ewing, "Ground Roll Coupling to Atmospheric Compressional Waves," Geophysics 16, 416–438 (1951).

[3] W. S. Jardetzky and F. Press, "Rayleigh-Wave Coupling to Atmospheric Compressional Waves," Bull. Seismol. Soc. Am. 42, 135–144 (1952).

[4] F. Press and J. Oliver, "Model Study of Air-Coupled Surface Waves," J. Acoust. Soc. Am. 27, 43–46 (1955).

[5] F. Press and M. Ewing, "Theory of Air-Coupled Flexural Waves," J. Appl. Phys. 22, 892–899 (1951).

[6] A. F. Espinosa, P. J. Sierra, and W. V. Mickey, "Seismic Waves Generated by Sonic Booms: A Geoacoustical Problem," J. Acoust. Soc. Am. 44, 1074–1082 (1968).

[7] T. T. Goforth and J. A. McDonald, "A Physical Interpretation of Seismic Waves Induced by Sonic Booms," J. Geophys. Res. 75, 5087–5092 (1970).

[8] J. A. McDonald and T. T. Goforth, "Seismic Effects of Sonic Booms: Empirical Results," J. Geophys. Res. 74, 2637–2647 (1969).

[9] M. D. Flohr and D. H. Cress, "Acoustic-to-Seismic Coupling Properties and Applications to Seismic Sensors," Waterways Experiment Station Technical Rep. EL-79-1 (1979).

[10] R. J. Donato, "Propagation of a Spherical Wave Near a Plane Boundary with a Complex Impedance," J. Acoust. Soc. Am. 60, 34–39 (1976).

[11] H. E. Bass and L. N. Bolen, "Propagation of Sound Through the Atmosphere: Effects of Ground Cover," Physical Acoustics Research Group University of Mississippi Rep. 78-01 (1978).

[12] C. I. Chessell, "Propagation of Noise Along a Finite Impedance Boundary," J. Acoust. Soc. Am. 62, 825–834 (1977).